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Review

The way forward: Can connectivity be useful to design better measuring and modelling schemes for water and sediment dynamics?

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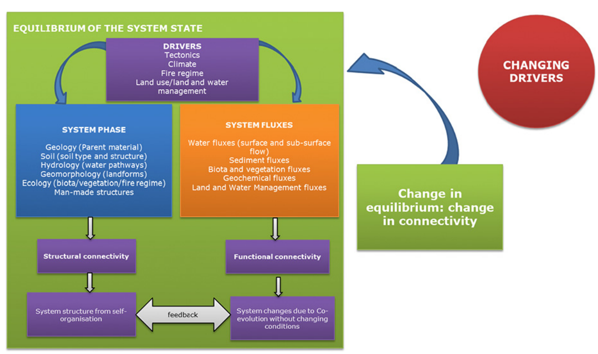
HIGHLIGHTS

- We introduce a conceptual framework for modelling and measuring water and sediment fluxes.
- System phases and fluxes are differentiated to enable quantification of connectivity.
- The mutual benefits of combining modelling and measuring to understand connectivity is shown.
- Necessary data for measuring and/or modelling water and sediment transfer is identified.

GRAPHICAL ABSTRACT



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ABSTRACT

For many years, scientists have tried to understand, describe and quantify water and sediment fluxes, with associated substances like pollutants, at multiple scales. In the past two decades, a new concept called connectivity has been used by Earth Scientists as a means to describe and quantify the influences on the fluxes of water and sediment on different scales: aggregate, pedon, location on the slope, slope, watershed, and basin. A better understanding of connectivity can enhance our comprehension of landscape processes and provide a basis for the development of better measurement and modelling approaches, further leading to a better potential for implementing this concept as a management tool. This paper provides a short review of the State-of-the-Art of the connectivity concept, from which we conclude that scientists have been struggling to find a way to quantify connectivity so far. We adapt the knowledge of connectivity to better understand and quantify water and sediment transfers in catchment systems. First, we introduce a new approach to the concept of connectivity to study water and sediment transfers and the associated substances. In this approach water and sediment dynamics are divided in two parts: the system consists of phases and fluxes, each being separately measurable. This approach enables us to: i) better conceptualize our understanding of system dynamics at different timescales, including long timescales; ii) identify the main parameters driving system dynamics, and devise monitoring strategies which capture them; and, iii) build models with a holistic approach to simulate system dynamics

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without excessive complexity. Secondly, we discuss the role of system boundaries in designing measurement schemes and models. Natural systems have boundaries within which sediment connectivity varies between phases; in (semi-)arid regions these boundaries can be far apart in time due to extreme events. External disturbances (eg. climate change, changed land management) can change these boundaries. It is therefore important to consider the system state as a whole, including its boundaries and internal dynamics, when designing and implementing comprehensive monitoring and modelling approaches. Connectivity is a useful tool concept for scientists that must be expanded to stakeholder and policymakers.

Contents

1. Introduction

Earth scientists seek to understand, describe and quantify water and sediment fluxes, with their associated substances like pollutants, across landscapes at multiple scales (Wolman and Gerson, 1978; Howard, 1982). The aim of the researchers has a temporal and spatial approach: from hydro-geomorphological processes triggered by a single rainfall event to the geological timescale of landscape evolution (Howard, 1982; Wang et al., 2006); and from the particle and soil aggregate scale up to the continental scale (Kirchner et al., 2001; Renschler and Harbor, 2002). In the past two decades, a new concept called connectivity has been used by the scientific community as a means to describe and quantify the influences on the fluxes of water and sediment at different scales: pedon, location on the slope, slope, watershed and basin (Parsons et al., 2015). The concept of connectivity and measurement scales are interrelated, because water and sediment transfers change according to the scale at which they are observed as a result of changing connectivity (Cammeraat, 2002).

Understanding connectivity enhances our understanding of landscape processes and allows for developing better measurement and modelling approaches. These better measurement and modelling approaches, in turn, lead to a better potential of implementing this concept as a management tool. The connectivity-based approach provides the potential for holistic solutions, which are compatible with the implementation of key EU policy directives, such as the Water Framework, Bathing Waters and the future Soils Directives (Croke and Hairsine, 2006; SD Keesstra et al., 2016). The connectivity-based approach serves different disciplines, from soil science, to geomorphology, hydrology, geology, ecology and atmospheric sciences (Pauling et al., 2006; Urban and Keitt, 2001; Savenije, 2009; García-Ruiz et al., 1995).

The pioneer use of the term connectivity was by mathematicians (Whyburn, 1931) and later by physicians (Shimbel and Rapoport, 1948). Within the Earth Sciences, the concept of connectivity was pioneered by biologists (Leake and Anninos, 1976), and has been used to describe relations amongst species (Henein and Merriam, 1990). Connectivity also contributed to advances in meteorology in the 1950s (Munk, 1950), and was soon used by soil scientists to describe chemical interactions in the soil column (Webber and Jellema, 1965). Connectivity transferred to other areas of science such as geology (Clark, 1973; Bonham, 1980), archaeology (Bronson and Asmar, 1975), chemistry (Bahnick and Doucette, 1988; Gerstl and Helling, 1987), and geomorphology and hydrology (Grisak et al., 1980; Burt and Gardiner, 1982). Since the beginning of the 21st century the concept of connectivity has been further elaborated in hydrology (Bracken and Croke, 2007) and geomorphology (Brierley et al., 2006), where connectivity is seen to act on different spatial directions, i.e. longitudinal (river channel), lateral (hillslope/floodplain-channel), and vertical (surface-subsurface) connectivity (Ward, 1989; Brierley et al., 2006; Fryirs et al., 2007). In recent years, the concept of connectivity has become increasingly prevalent (López-Vicente et al., 2015; Buendia et al., 2015; Marchamalo et al., 2016) as a tool to understand the processes in Earth Science.

In the field of water and sediment transfer, scientists have been struggling to find a way to quantify connectivity. Most studies remain conceptual (Bracken et al., 2013), or use connectivity to describe and understand the system better a qualitative way (Bracken et al., 2015). Other uses of the concept include assessing connectivity through a relative index used to compare different compartments of a catchment (Cavalli et al., 2013; Heckmann et al., 2015). The current view on connectivity identifies structural connectivity, defined as the extent to which landscape units (at multiple spatial scales) are contiguous or physically linked to one another; and functional connectivity, defined as the way in which interactions between multiple structural characteristics of the system in question affect geomorphic, ecologic and hydrologic processes (Wainwright et al., 2011). In this study, the authors also acknowledge that there is an interaction between structural and functional connectivity, which causes problems in longer term studies, because structural connectivity becomes functional when the time span is long enough (López-Vicente et al., 2017). This in turn, causes problems defining the way the processes and finally connectivity can be assessed in the field or in a modelling effort. These issues call for a new approach to describe and use the concept of structural connectivity that can be applied to all temporal and spatial scales.

The aim of this paper is to review State-of-the-Art connectivity concepts and adapt the existing knowledge on connectivity better to understand and quantify water and sediment transfers within catchments. The objectives are: (i) to give an overview of the State-of-the-Art in the field of water and sediment connectivity; (ii) to propose a framework to describe catchment system dynamics from a connectivity point of view; (iii), to discuss the implications of this framework for measuring and modelling of water and sediment fluxes; and (iv) to identify priority research issues to advance our understanding of measuring and modelling approaches using the connectivity concept.

2. Water and sediment connectivity concepts: review and scientific gaps

2.1. A review of the role of connectivity in water and sediment transfer

Under natural conditions, connectivity of the hydrological and erosional systems is driven by geological and geomorphological conditions (e.g. parent material, tectonics, relief, landforms), climate (e.g. rainfall and temperature) and biota (vegetation and fauna). In addition, human activities such as agriculture, grazing, fire, mining, and roads may have profound impact on structure and function, and hence connectivity, of geomorphic systems (Marsh, 1864).

Connectivity describes the degree to which flows of water and sediment at the aggregate, pedon, slope and watershed scales is facilitated. However, dis-connections are more present in the hydro-geomorphological system than connections due to short duration of the rainfall events (Strohmeier et al., 2016), or interferences of relief, fauna, flora or reservoirs in river (Fryirs et al., 2007). This (dis)-connectivity is why runoff and sediment yield are not just the sum of sources, and why the runoff generation conceptual model of Horton (1933) (Fig. 1a) is rarely found in Mediterranean and humid landscapes (Pearce et al., 1986; Kirkby, 1988; Bonell, 1993; Croke et al., 1999), where infiltration rates tend to be higher than the rainfall intensities. Yair and Lavee (1985) have shown in arid regions that runoff generated in the upper parts of the slopes does not reach the river channels, because it infiltrates into the colluvium, and is therefore disconnected from the drainage network (Fig. 1b). Another example is related to temperate regions where runoff is generated by subsurface flow, while surface flow rarely occurs on the slopes (Hewlett, 1961; Fig. 1c). Nevertheless, streamflow in the channels is present due to saturation of the soils at the base of hillslopes (Fig. 1d; Hewlett and Hibbert, 1967; Hibbert and Troendle, 1988). Soil saturation patterns are, therefore, another important driver for connectivity (Cammeraat, 2002). Moreover, connectivity is strongly influenced by climatic seasonality. In Mediterranean regions, for example, soil moisture patterns are only important for connectivity during the wet season, i.e. when the system behaves like those in temperate climates (Kirkby et al., 2002).

Biota also plays a key role, because it can both enhance and limit connectivity (Stavi et al., 2018). Vegetation is a key factor affecting detachment, transport and sedimentation processes; plant cover reduces raindrop impact, covers the soil with litter, contributes to soil development and increases infiltration capacity of soils (Fig. 2a; Cerda, 1999). A patchy distribution of vegetation, therefore, generates sink and source areas for water and sediment (Fig. 2b; Cerdà, 1997). Plant roots influence subsurface connectivity by creating preferred pathways of subsurface flow (Gyssels and Poesen, 2003). Vegetation stems, reduce overland flow velocity, promote infiltration and reduce surface connectivity (Zhao et al., 2016). Furthermore, animals, wild or domesticated, may also alter connectivity (Trimble and Mendel, 1995; Evans, 1998). For example, wild boars activate sediment availability by burrowing, while ant nests contribute to deep infiltration and overland flow disconnectivity (Cammeraat et al., 2002). Beavers impound rivers by building dams, increasing percolation and reducing streamflow and sediment transport (Stanford and Ward, 1993; Westbrook et al., 2006; Nyssen et al., 2011; Smith, 1997).

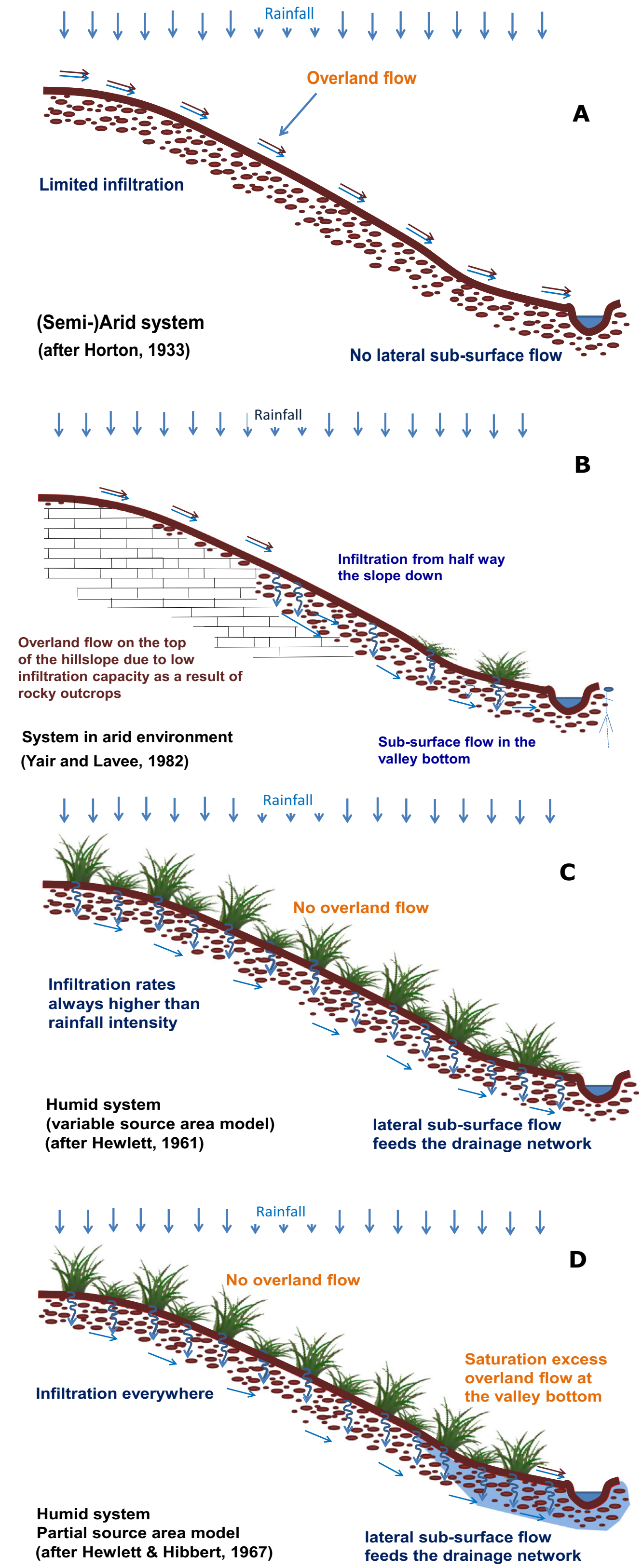

Fig. 1. Conceptual Runoff generation models. A: In (semi) arid systems water (with eroded sediment) flows to the drainage network as overland flow (model after Horton, 1933). B: In arid systems with rocky hillslopes overland flow at the hillslope tops; some infiltration and through flow to the drainage system in the valley bottom (model after Yair and Lavee, 1982). C: In humid system (after Hewlett, 1961). No overland flow due to the infiltration capacity always being higher than the rainfall intensity. The drainage network is fed by subsurface flow. D: In partial source area model in humid systems after Hewlett and Hibbert (1967). Similar to c, however due to saturation of the valley bottom saturation overland flow can occur.

Human actions can greatly influence connectivity; most of the surface of the world has been altered by human activity managing landscapes and water courses (Hawtree et al., 2015; Poeppl et al., 2015). The expansion of agriculture resulted in a geomorphic system managed by humankind and domesticated animals (Deluca et al., 1998). Long-inhabited landscapes, such as those around the Mediterranean, are far from natural; they can be referred to as man-made landscapes (Blondel, 2006). More recently, nature conservation policies have had influences on the landscape and thus, connectivity (Panagos et al., 2016). These impacts now form an essential part of the landscape-forming parameters and therefore need to be incorporated when studying water sediment and transfer. As Nir (1983) suggested, we need to think of landscapes as human-driven landforms.

Most of the consequences of landscape changes induced by humankind regarding connectivity have been unintentional. Deforestation, besides supplying wood, increases surface runoff (Anselmetti et al., 2007; Zhao et al., 2016). Similarly, land abandonment leads to reduced connectivity through unintended natural vegetation recovery. Land abandonment, moreover, changes vertical connectivity (Fryirs, 2013). Under tillage, the soil is permeable, and rainfall can wet the soil easily, thereby reducing surface runoff. Contrarily, when the soil is no longer tilled, infiltration is initially much reduced. Only after some years of soil recovery soil infiltration recovers under the influence of biota (Fig. 3). Other features that unintentionally enhance vertical or lateral connectivity include forest roads, tractor tracks and soil compaction at field gates (Cao et al., 2015). Other man-made structures and actions, however, (intentionally) reduce connectivity. These structures and actions include terrace construction, soil and water conservation, contour afforestation, vegetation recovery, ploughing, dams, and irrigation systems that generally reduces connectivity (Pringle, 2003; Poeppl et al., 2015), while agricultural management strategies can work either way depending on the type of activity (Borrelli et al., 2015).

Connectivity can be considered an emergent property of the landscape system, which results from the complex interaction of the system components or structures: vegetation, soils, topography and landforms (Bracken and Croke, 2007; Wainwright et al., 2011). In this sense, connectivity evolves as a result of water and sediment fluxes. For example, connectivity can be increased by intense rainfall events which remove vegetation from river channels (Sanjuán et al., 2016), or by natural forest fires which remove vegetation from the slopes (Nunes et al., 2018a). Landslides and earthquakes can contribute to create lakes on slopes and in channels, which might disconnect parts of the fluvial system (Lanckriet et al., 2016). Land abandonment leads to the lack of terrace maintenance, which may cause them to collapse and turn them from structures that reduce connectivity to structures that enhance it (Arnáez et al., 2015). It can, therefore, be said that while geomorphological evolution is driven by water and sediment fluxes, feedback effects induced by the evolving landform in turn affect water and sediment processes (Tian et al., 2015; Poeppl et al., 2017). Similarly, vegetation and connectivity can co-evolve through interactions between them (Fig. 4; Saco and Moreno-de las Heras, 2013). A similar feedback process can be observed in fluvial systems, that change under influence of catchment management, river management and geomorphic processes (Poeppl et al., 2015, 2017; Fig. 5). The sediment connectivity in the channel (the longitudinal connectivity) is the result of processes occurring on the hillslope, influx of sediment to the channel network; and the processes in the channel itself. These in-channel dynamics are impacted by management actions both in the channel itself as well as in the catchment. Land-management changes in the catchment such as reforestation will result in a changed balance in the amount of sediment and water coming to the channel. In this case, initially, the amount of sediment will be more reduced than the amount of water, causing the river to incise (Keesstra et al., 2005). This change in channel morphology in turn, has an impact on the lateral connectivity, because the channel network becomes less connected to the floodplain due to this incision. Dams have direct impact on the longitudinal connectivity, however, they also change vertical connectivity in the up and downstream river reaches by aggradation and incision, respectively (Poeppl et al., 2015). These management interventions, both in the channel as well on the hillslopes do not only have immediate consequences in terms of connectivity, but also have long-term effects that alter the system through feedback processes (Fig. 5).

2.2. Recent developments in connectivity research

Over the past two decades, the concept of connectivity has received increasing attention to address the scaling problem in hydrology (Bracken and Croke, 2007; Bracken et al., 2013, 2015; Parsons et al., 2015) and in geomorphology, where it first appeared as geomorphic (hillslope-channel) coupling (Harvey, 2001, 2002). In the context of sediment budgets, connectivity has also been seen as an actor, that controls the link between hillslope and catchment scales in terms of the (fluvial) sediment yield (Brierley et al., 2006; Slaymaker, 2006). Internal sediment dynamics and catchment sediment yield are linked, amongst others, to the configuration of sediment stores and sinks, and to what Fryirs et al. (2007) term buffers, barriers and blankets that disconnect sediment cascades.

While in some cases, the conceptualization of connectivity draws on ecological theory, recent reviews suggested that a major problem has arisen due to the differences in the definition of the term and concept by hydrologists and geomorphologists (Bracken et al., 2013, 2015). Developments in the theory of connectivity have emphasized the effects of “static” or structural as compared to “dynamic” or functional components (Wainwright et al., 2011). These two terms are well established in the scientific community working on connectivity, but they seem to create problems when implemented on longer time scales.

Bracken et al. (2013) recognized that some confusion has arisen from the “functional” terminology, and have thus suggested that it be replaced by the term “process-based” connectivity. However, the renaming did not solve the issue of structural connectivity becoming functional connectivity after long time spans. Therefore, there is still no satisfactory solution to the problem of scaling in water and sediment connectivity.

Although the connectivity concept provides a skeleton that allows an understanding of the transfer of water and sediment through landscapes, there remains a need to understand the role measurement scales play in studies on the redistribution of water and sediments across the landscape. Fig. 6 provides an example of how different natural and human drivers influence the connectivity of a catchment. The development of technologies for assessing spatio-temporal patterns of environmental parameters has been fast, but has not facilitated the advancement of the connectivity concept. Distributed methods of instrumentation will increase the availability of high-resolution spatial and temporal geographical information and enable a more thorough evaluation of the condition of the system and the fluxes of water and sediment through the landscape. Examples of such developments are the use of satellites for soil moisture mapping (Wang and Qu, 2009), overland flow sensor networks (Masselink et al., 2016) or radionuclides to assess sediment pathways (Mabit et al., 2014). In such studies the sampling design should be developed coherently with the understanding of the connectivity of the study area. In parallel, modelling techniques for evaluating connectivity have also advanced. There are distinctions between models that explicitly consider connectivity (Johnes and Heathwaite, 1997; Lane et al., 2004; McGuire and McDonnell, 2007) and those that allow it to emerge as a function of model behaviour (Lesschen et al., 2009).

During the past decade, increased interest on the use of connectivity to explain observed behaviour of hydrologic responses has led to an increasing body of publications in this area. Though models using connectivity concepts are still limited, there are several research groups that have developed modelling approaches that capture several aspects of functional and structural connectivity to improve both the

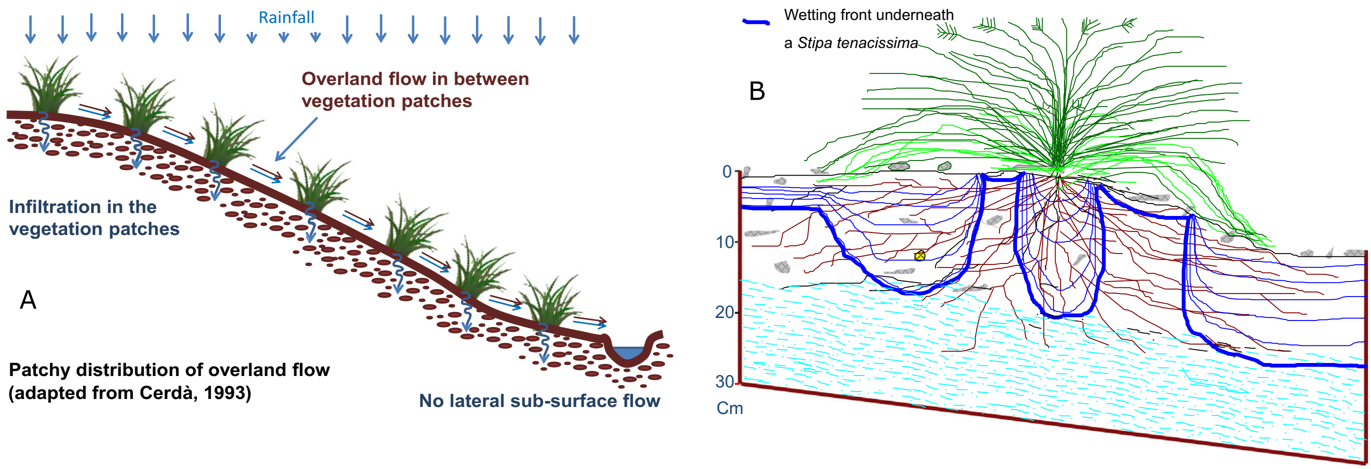

Fig. 2. Runoff generation in Mediterranean type ecosystems with a patchy distribution of the vegetation (*Stipa tenacissima L.*) in areas with 350 mm of mean annual rainfall (potential evapotranspiration 1200 mm y^{-1}). Based in Cerdà (1993) and Cerdà (1997). A.: Patchy distribution in a Mediterranean climate. Overland flow in the inter patches; infiltration and sediment deposition in the vegetation patches. Little to no water reaches the drainage system as subsurface flow. Depending on the rainfall intensity some water and sediment will reach the drainage system through overland flow. B: Wetting front underneath an isolated *Stipa tenacissima* tussock. The wetting front clearly indicates the influence of the patchy vegetation on infiltration and the subsequent soil moisture profile. Based in Cammeraat et al. (2010).

understanding of catchment response behaviour as well as predictions (Birkel et al., 2010; Callow and Smettem, 2009; Lane et al., 2009; Lesschen et al., 2009; Meerkerk et al., 2009; Reaney et al., 2014). Traditional models that use this type of approach include the earliest versions of the Curve Number method, originally conceived to summarize the impacts of soil wetness on hydrological connectivity for small catchments (Garen and Moore, 2005). TOPMODEL uses a more sophisticated approach to capture changes in hydrological connectivity from time-varying changes in saturated areas resulting from soil water accumulation (Beven and Freer, 2001). There are also erosion models that summarize sediment connectivity as the relationship between soil detachment and transport, such as the "P" factor in RUSLE at the field scale (Renard et al., 2011) or the sediment delivery ratio at the catchment scale (Lane et al., 1997). More recent examples of this type of approach include efforts to parameterize time-varying changes to connectivity at smaller scales, such as microtopography and its influence in hillslope discharge (Antoine et al., 2011), soil-water repellent patches linked with hillslope surface runoff in burnt areas (Nunes et al., 2016), simulation of streamflow discharge as a function of the spatial frequency of hillslope areas hydrologically connected to streams by shallow subsurface flows (Smith et al., 2013). Other recent modelling approaches include studies that capture nonlinear streamflow response for temperate and boreal environments by using a conceptualization of the hydrological connectivity of the catchment, which links the hillslopes to the saturated riparian zones and the underlying groundwater (Soulsby et al., 2016; Blumstock et al., 2016).

Much effort has gone into simplifying the analysis of connectivity to provide indices that can be easily applied (McRae et al., 2008). Such indices rely, for example, on apparent properties of permeability fields in (groundwater) hydrology (Knudby and Carrera, 2006), and on

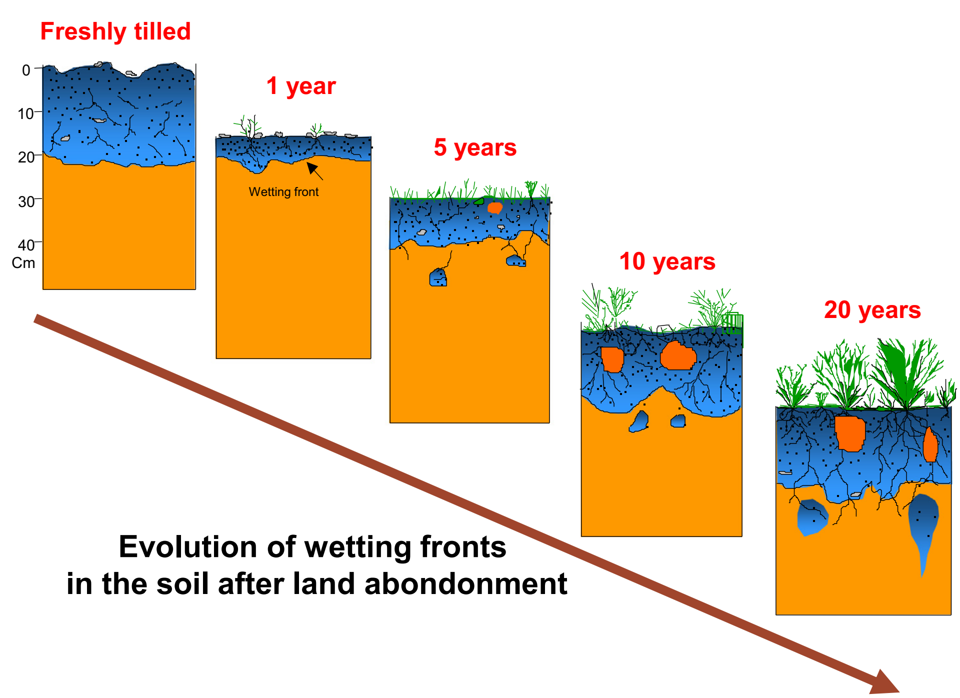

Fig. 3. Infiltration and subsequent wetting fronts under tillage and different stages of abandoned land. The wetting fronts are a result of simulated rainfall at 55 mm h^{-1} during one hour. The graphs were drawn immediately after the rainfall (based on Cerdà, 1997).

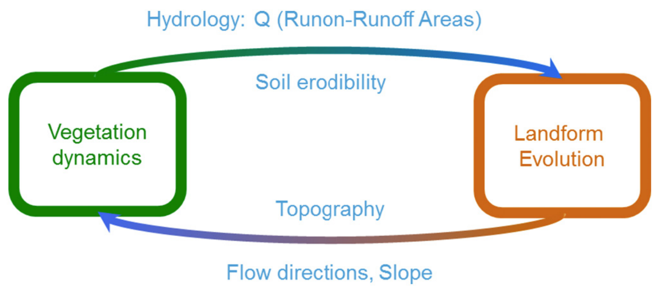

Fig. 4. System dynamics and co-evolution of the system processes and structures, and the associated changes in system function (adapted from Saco et al., 2007).

estimations of effective contributing areas (delineated and optionally weighted from DEMs and derived parameters) in geomorphology (Borselli et al., 2008; Cavalli et al., 2013). Some efforts have also been made to combine hydrological and sediment connectivity (Reid et al., 2007). However, no single technique has emerged as being useful in all studies (Ali and Roy, 2009). Some approaches to quantify connectivity remain merely conceptual (Fryirs, 2013) and need further development, for example the use of graphs as models and data structures for describing and analysing hydrological and/or geomorphic systems with different degrees of connectivity (Gascuel-Odoux et al., 2011; Phillips, 2011; Heckmann and Schwanghart, 2013). However, all these indices are only concerned with the relative quantification of connectivity for a given landscape, and therefore not useful to compare different systems. Bracken et al. (2013) suggested that one problem lies in the need for a better conceptualization of indices, and their underpinning, using a broader data and modelling basis.

Summarizing, the following issues can be listed: the concept of connectivity is too abstract, and therefore difficult to implement in measuring and modelling of real catchment systems. Secondly, the way structural connectivity is described is confusing and especially on longer time scales is not well defined. Thirdly, the new emerging methodologies such as high resolution DEMs and tracing studies form a new opportunity to look into how they can be used to link different scales. These new methods potentially forms the opportunity to incorporate small scale processes on the larger scale. Lastly, none of the emerging indices describing connectivity has proven to be useful in all environments.

The issues raised in this section call for a new approach to use the concept of connectivity to make it easier to use in actual research projects. The different processes acting at the catchment scale should be carefully identified and separately assessed to enable a better understanding of the system connectivity. The identification of the key processes that are fundamentally important for catchment hydrologic and sediment connectivity may facilitate the generation of improved measuring strategies and modelling efforts.

3. A framework to describe catchment system dynamics from a connectivity perspective

The approach we take for the description of connectivity in water and sediment transfer is to first look at a catchment system and examine how the system works.

We assume that the current state of a natural system is the result of processes that have been interacting over a long period of time to shape the landscape. The characteristics of a system such as geological structure, parent material, soil types, climate, water transfer paths and biota, (both vegetation as well as fauna), typical fire regime and typical land management in landscapes have caused the current state of the catchment system through a process of self-organisation (Troch et al., 2015). This state includes the natural variability as a consequence of the internal changes of the system (Chorley and Kennedy, 1971). If these structures that determine the state of the system remain reasonably stable over time, we argue that the system is in equilibrium. However, we need to recognise that this "equilibrium" state is not completely static in natural systems (Chorley and Kennedy, 1971). That is, the variability of the state components has a stable range over

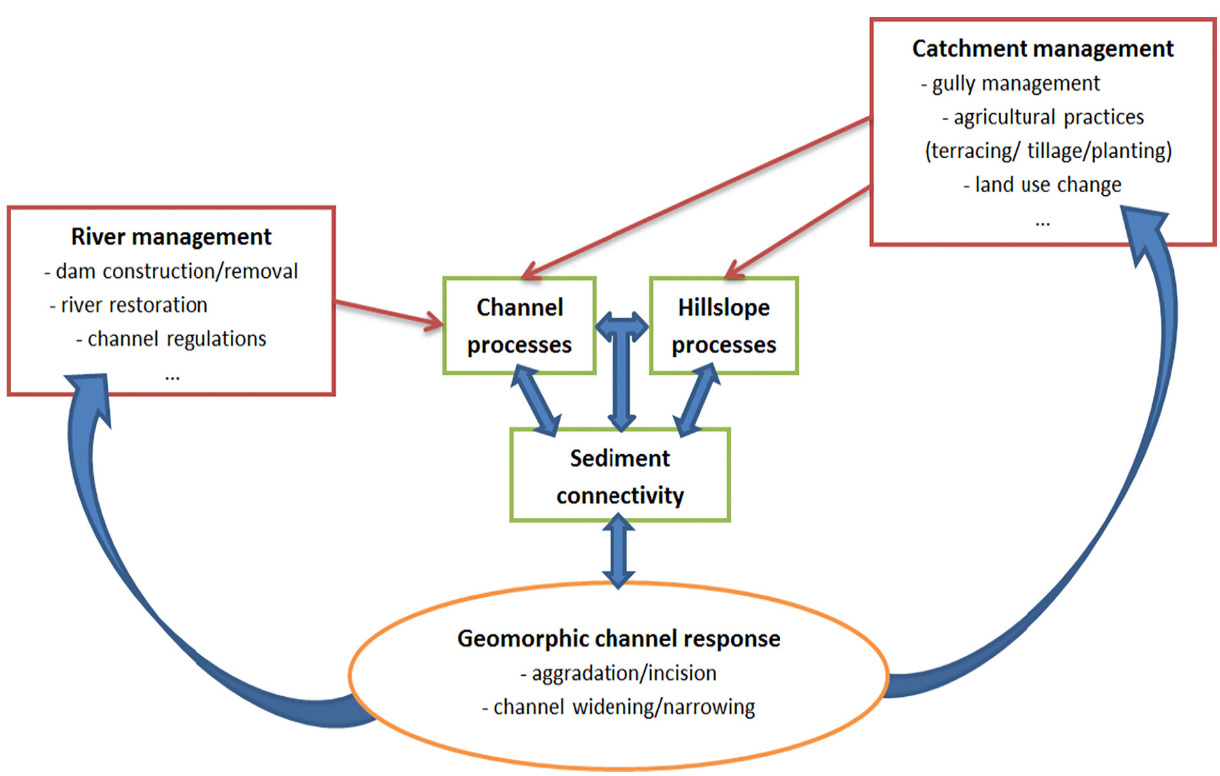

Fig. 5. Schematic representation of the influence and feedbacks in river and catchment management on sediment connectivity and channel morphology in small- to meso-scale fluvial systems (adapted from Poeppl et al., 2017).

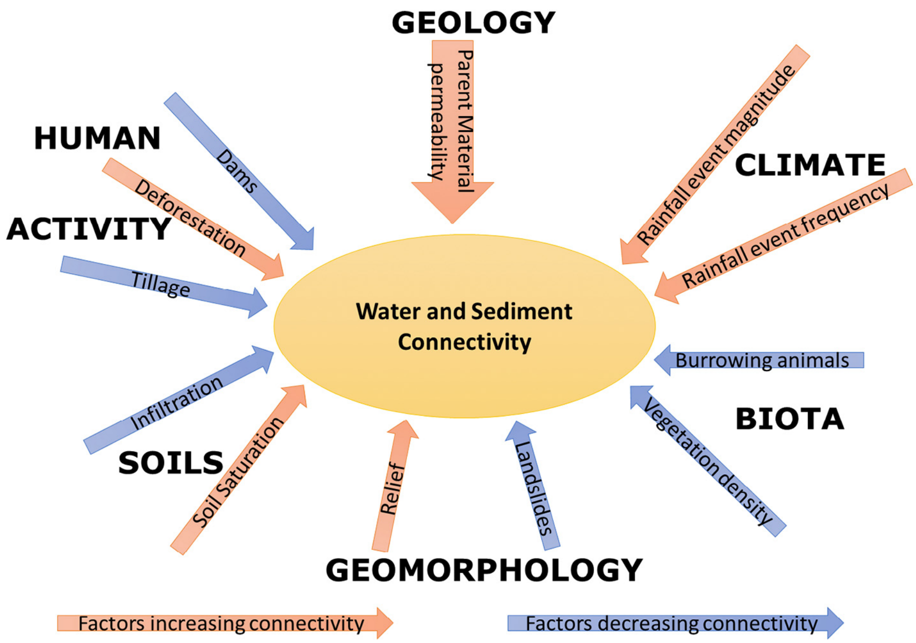

Fig. 6. Schematic representation of the increasing and decreasing factors in geology, climate, biota, geomorphology, soils and human activities on water and sediment connectivity.

a period of time that is also characteristic for each system. As an example, in a Mediterranean-type Ecosystem climate variability is known to be large, and landscape-forming events are known to be rare (Butzer, 2005). Therefore, the timeframe in which all variability of the system occurs is long. However, at a given moment when the characteristics of the system are assessed in the field, we can measure only a snapshot of the system state: the current phase in which the system is at that particular moment. We argue that this system phase defines the structural connectivity at that particular moment in time, which is from a temporal point of view dimensionless.

The conceptual framework that follows from these definitions of equilibrium and system states serves to generate a better understanding of catchment system dynamics in terms of water and sediment transfer by breaking apart the system dynamics into system phases and system fluxes. Describing catchment characteristics and behaviour using phases (snapshots of the system state at any given time) and fluxes (describing the transfer of water and sediment within the system), is a way to improve the understanding of the concepts of hydrological and sediment connectivity as described in previous research by Bracken et al. (2013, 2015). Improving our understanding of the individual phases and fluxes of the system will allow us to identify the key aspects that we should measure and include in holistic models of catchment connectivity. In addition, the individual parts (phases and fluxes) can be measured and therefore put in a model to quantify the system dynamics in a more holistic way; which will therefore contribute to quantifying the connectivity of the system.

In this conceptual framework (Fig. 7), it is argued that, over time, when the system is at equilibrium (Saco and Moreno-de las Heras, 2013), the system fluxes will remain within certain limits in response to the variability in the system state. This condition means that the system phase may change; but over a longer period of time, the system exhibits the same range of phases is stable. This idea is similar to theories described in the literature such as channel-forming discharge (which characterizes the driving variable of the system) in fluvial geomorphology and hydrology (Wolman and Miller, 1960; Doyle et al., 2007) where extreme events also determine the boundary conditions of that system.

Structural connectivity has previously been used to refer to the system's spatial patterns at any given time. In our framework these patterns are encapsulated amongst the system phases and affect the transfer of water through the system's flow paths (Turnbull et al., 2008; Bracken et al., 2013). The structural connectivity is, as mentioned earlier, constantly changing under the influence of coevolving system components over time, and thus an emergent property of a self-organizing system. At any given time, structural connectivity can also be considered as being determined by all the system components (or structures) that are potentially observable, though sometimes very difficult to measure (for example some characteristics of soil spatial patterns, including soil hydraulic conductivity, soil depth, distribution of soil fauna, chemical properties, etc.). We argue that these structures emerge in response to fluxes within the system (water, solutes, sediment, biotic and atmospheric fluxes) that are within normal range of driving conditions/variables (and therefore characterised by a given range of variability); and are determined by the system functional response to these external fluctuations (for example climatic variability). The combined effect of all these fluxes gives rise to what has been defined as functional connectivity over a specific timeframe, which depends on the research question at hand. In this way, structural connectivity is influenced by functional connectivity and vice versa, as was also mentioned by Wainwright et al. (2011) and Bracken et al. (2015). The interacting phases and fluxes represent how the system state co-evolves and fluctuates due to the impact of water, sediment, biota, and chemical fluxes it is exposed to without changing the boundary conditions. We should, however, mention here that in some systems the equilibrium state can shift without external forcing, but instead, as a consequence of internal dynamics pushing the system into a different equilibrium. Although the presented conceptual framework does not account for this type of system, the concept of phases and fluxes remains valid, and can be adapted to deal with this type of system.

The connectivity conditions depend on the mean variation of external drivers such as tectonics, climate, natural fire recurrence, and a typical, stable land and water management conditions that the system is subjected to (Fig. 7). However, when the boundary conditions of the system change, such as changes in tectonics, prevailing fire regime, or the way the land and water resources are managed, the equilibrium will be disturbed. The system will subsequently adjust itself to a new equilibrium, which may have very different characteristics even if the change in the system is not very distinct (Chorley and Kennedy, 1971; Fig. 7).

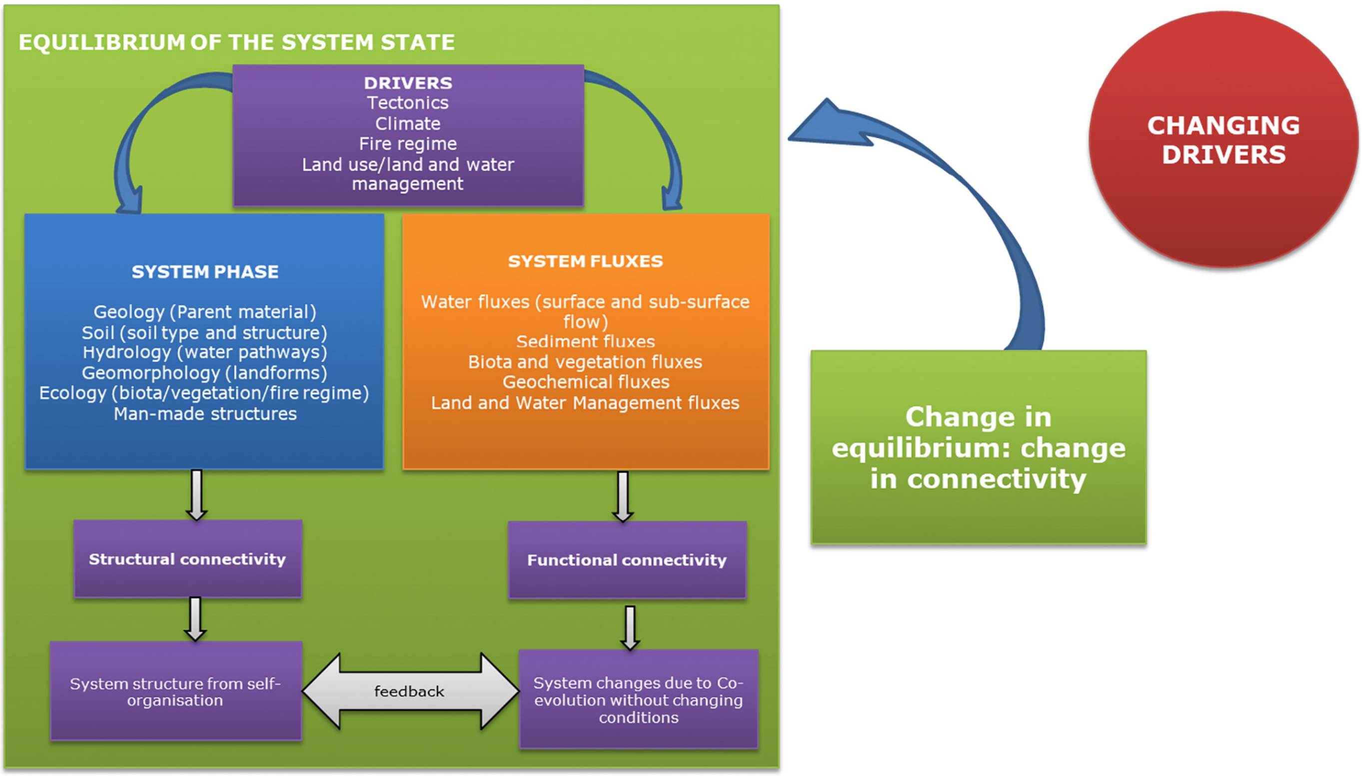

Fig. 7. Framework for a systems approach in sediment and water transfer: components and interactions.

4. What does this framework mean for measurement and modelling approaches to connectivity?

In the first part of this section, we discuss the usefulness of this conceptual framework (Fig. 7) for developing better sampling schemes and better measurement techniques. Second, we discuss the usefulness of this framework for developing better models by incorporating this more holistic way of looking at catchment system dynamics. These models should take this holistic approach into account without becoming too complex. In the second part, we evaluate if connectivity indices can make the difference we need; discuss if the conceptual framework helps to combat difficulties with both temporal and spatial scaling (Fig. 8). Third, we discuss if the framework helps to quantify a system in equilibrium and if it can capture all the dynamics in the system. Finally, we evaluate the best approach for studying three case studies that have been, or are being pushed out of their equilibrium and how we observed the changes these systems went through as a result of an external driver.

4.1. Measurement approaches

To solve land and water-management related problems at catchment scale it is important to quantify fluxes of water, sediment and associated substances. Connectivity may help with this quantification. However, when we ask ourselves the question of how to measure connectivity, we would like to argue that we cannot measure connectivity directly. As was demonstrated in the previous section, connectivity was presented as an end-result, an emergent property, of the whole system. The fluxes in the system over a specified time span depending on the research question, can be seen as the functional connectivity (Fig. 7) e.g. how a system will react to a short flux such as a rainfall event, or a long flux such as changing vegetation cover over a season. The phase of the system state at a certain moment in time is the structural connectivity (Fig. 7). This means that if we want to quantify connectivity we have to measure the different variables in a catchment that we know are the key drivers for connectivity in the system. We argue that the systems approach as presented in the conceptual diagram (Fig. 7) can help to solve this problem. The systems approach (Gregorio et al., 2015; Suckall et al., 2015) has been widely used, specifically for research questions that ask for a holistic approach towards a certain problem. This is true for systems where a subsystem cannot be studied individually as it is influenced too much by the surrounding subsystems. Examples of these systems can be found in ecology (Hopkins et al., 2011; Anandhi et al., 2016) or social sciences (Kunz and Moran, 2016) where the concept of connectivity has been used and accepted for much longer. For an effective use of the system approach, we need to integrate knowledge from different disciplines related to the dynamics of interest, such as geomorphology, soil science, hydrology and biology, to be able to assess the states and fluxes of sediment and water in the system.

What does this mean in terms of designing better sampling schemes for water and sediment fluxes? By acknowledging the system phases and fluxes as described in Fig. 7, each part of a system becomes a measurable unit. Depending on the research question an efficient and informative sampling scheme can be generated for these separate units. However, the different scales for which we have measurement devices may be insufficient to measure the fluxes of the same substance (e.g. water), both temporally as well as spatially for multiple scales.

When the line of thought of the framework in Fig. 7 is followed, we must split the system state into snapshots of the state; phases and fluxes. In recent years, large advances have been made towards generating high resolution data that can represent the phases. Especially for measuring the structure of the landscape, new methods are continuously improved. The phase, a snapshot, can be obtained from (high-resolution) digital elevation models that are created using (terrestrial) laser scanning or unmanned aerial vehicles (Westoby et al., 2012; Nadal-Romero et al., 2015). Digital Elevation Models (DEMs) of relatively large areas (>1 km^2) can now be obtained with centimeter resolution and accuracy. With these high-resolution photographs, features that increase or decrease connectivity are more easily detected.

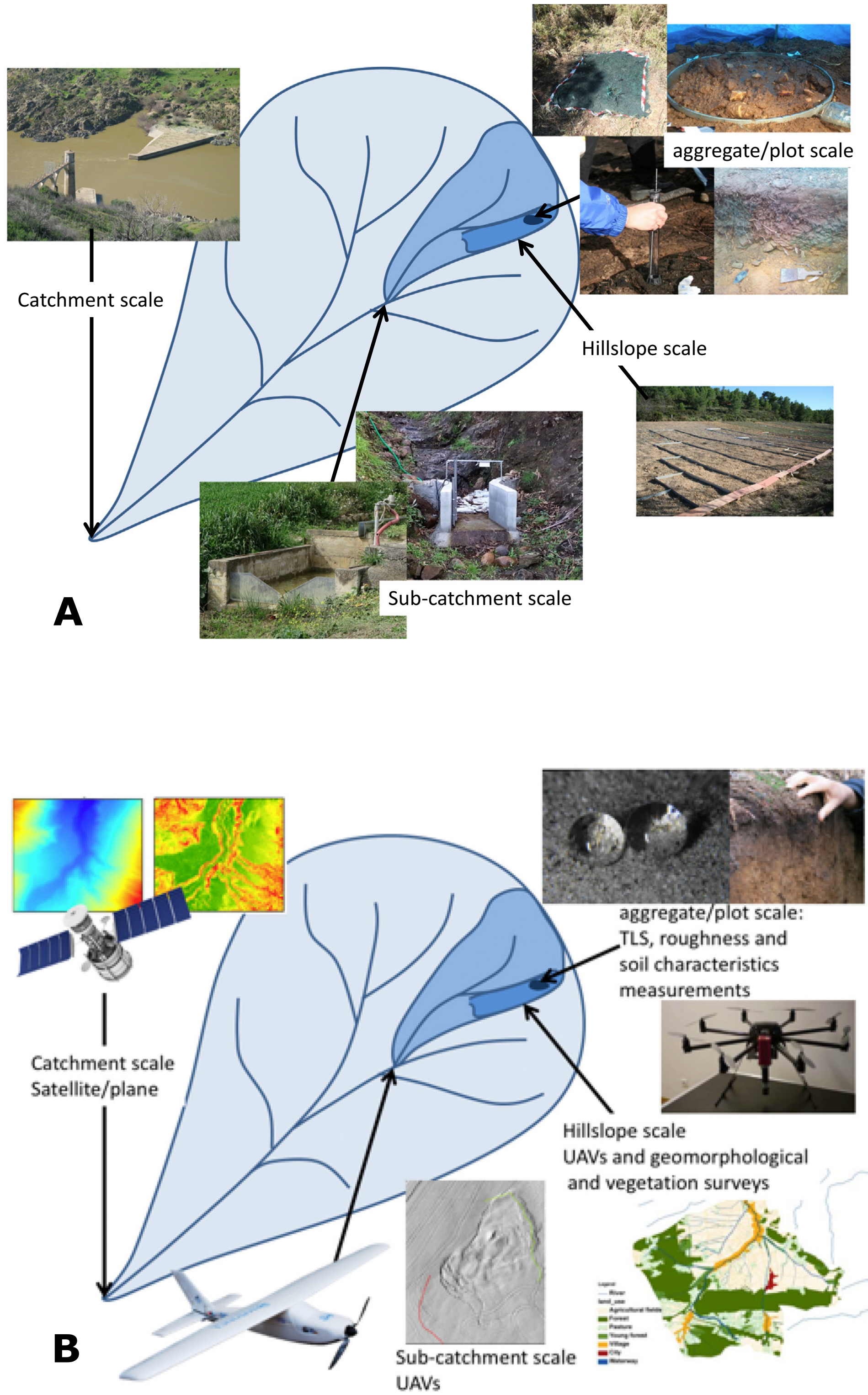

Fig. 8. Some examples of different measurement techniques for different scales: A: measurement techniques for fluxes: at aggregate scale and plot scale measurements devices such as a minidisk infiltrometer and rainfall simulators are used; at hillslope scale runoff and erosion can be monitored using Gerlach collectors; at sub-catchment scale small flumes are generally used to measure discharge and suspended sediment yield; in major rivers very large monitoring structures are used. B: Measurement techniques for phases: at aggregate scale and plot scale soil measurements, surface characteristics measurements; at the hillslope scale Unmanned Aerial Vehicles (UAV) multi-rotors and vegetation and geomorphological mapping; on sub-catchment scale: fix-wing UAVs, on catchment-scale: Satellite and manned plane imagery.

Furthermore, repeat surveys of these kinds can accurately give erosion and deposition rates over large areas. Due to the accuracy of the current DEMs, for now, these DEMs of Difference (DoDs), are limited to areas where large changes have taken place or where the landscape is not affected by agricultural practices like tillage. For the coming years, however, spatial resolution will further increase, while measurement errors will decrease, making DoD methods available in more areas. These data enable the linkage of small-scale processes to large scale processes. In Fig. 8a a cascade of the assessment of the phases on different scales is depicted for one set of data acquisition tools.

Other characteristics of the phase such as geology, soil and vegetation characteristics have their own set of assessment methodologies. Ranging from satellite imagery to field surveys (vegetation) and soil mapping surveys (catchment scale) to soil description (plot scale) to the smallest scale, the aggregate scale (Mamedov et al., 2017; Arjmand Sajjadi and Mahmoodabadi, 2015).

In terms of measuring fluxes of water and sediment in landscapes (see Figs. 7 and 8b) there are spatial gaps. For each scale within a catchment there are many established methodologies (Fig. 7b). For the catchment scale, there are methodologies such as discharge, suspended sediment and bedload transport measurement (Yuan et al., 2015; Grimaldi et al., 2015; Taguas et al., 2015). For the plot-scale many well-known methodologies are available, such as rainfall simulations (Ries et al., 2013) and other plot experiments such as infiltration and preferential flow path assessment (León et al., 2015).

However, methodologies to link the aggregate and plot scale to the catchment scale are scarce. Recently, some methodologies have been developed for getting a grip on relationships between the states of a hillslope and water transfer (Masselink et al., 2016), or in channel sediment transport using hysteresis loops (Sherriff et al., 2016), and on sediment fluxes on hillslopes using tracers (Alewell, 2014; Mabit et al., 2014). Most of these measurement techniques have been developed for a certain scale and lump the processes that are happening within the unit that is under study. Therefore, it is important to assess the suitability of each method when selecting the sampling approach for a study, including the precision and accuracy of the method at each scale of measurement, but also that the method of measurement will catch the whole variability of the process.

One example of a methodology which has the potential to bridge the spatial gaps in measurement approaches is water and sediment tracing and tracking, which has been increasingly applied for the past years. For water tracing, often the goal is to determine the various sources of the discharge of a catchment, using a variety of isotopes (Kendall and McDonnell, 1998). For sediments, a whole array of tracers exist, both naturally occurring in the soil, as well as those actively applied to the soil (Guzmán et al., 2013). These water and sediment tracer experiments have not often been combined with high-resolution structural measurements, which is where large advances can be made over the coming years. Multi-year tracking of sediments, combined with measured elevation changes from high-resolution topography can greatly increase both our understanding of catchment sediment dynamics and of connectivity. Multi-year tracking allows for determining “virtual” velocities for sediments, depending on e.g. hillslope position and antecedent conditions (Slaymaker, 2006; Wainwright et al., 2008).

The connectivity framework as described in Fig. 7 can link different fluxes with the phases in which the system state is. The exact implementation still needs to be developed. However, the framework aims to link different scales and associated methodologies to come to a comprehensive understanding of the systems' functioning. One example of how phases and fluxes can be integrated using novel techniques is shown in the recent study by Masselink et al. (2016). The phases of the system were measures using high resolution DEMs obtained by Unmanned Aerial Vehicle (UAV) orthophotos taken in multiple years and on different flying heights (different spatial resolutions). On the ground vegetation and soil type were assessed. The fluxes were measured using overland flow sensors on the hillslope and traditional pressure transducer for the catchment scale. The measured phases and fluxes were integrated using graph theory for obtaining information about the interaction between the phases, the drivers and the resulting fluxes. Sediment fluxes were measured using tracers (rare earth elements, Masselink et al., 2017). Tracing methodology form a new window of opportunity to assess sediment fluxes on slopes. In most studies sediment fluxes are only derived from plot-scale experiments, modelling based on plot-scale experiments, or sediment yield measurements in the drainage system. Tracing experiment using a variety of methodologies of natural and applied tracers can give insights on sediment movement on the intermediate scale that is needed to understand the system dynamics on a hillslope (Smith et al., 2015).

4.2. Modelling approaches: emergent property or imposed values?

We argue that, ideally, connectivity should be an emergent property of process-based models with sufficient spatial and temporal resolution (Nunes et al., 2018b). That is, given enough temporal and spatial resolution, and a detailed representation of all relevant processes in the model, the simulated water and sediment fluxes would reflect the connectivity of pathways in the model domain. However, it is impossible to represent all micro-scale variability in models. For coarser models often used for management, it is impractical to even represent variability within fields or at the sub-daily scale. In these cases, the concept of connectivity can be used to improve models and to define “equivalent or effective” parameters that capture the effect of connectivity at spatial and temporal scales smaller than the model resolution (see the discussion by Bracken et al., 2013) by using for instance a connectivity function for roughness, vegetation or an index of connectivity (Antoine et al., 2011). Models should be utilised to model connections between hillslopes and streams in terms of sediment, making use of the data collected at various spatial and temporal scales, preferably including sediment transport data at various scales as well. The system framework defined in Fig. 7 can be used to determine which of the fluxes and transitions between phases can be expected to emerge from model behaviour at its set resolution, and which should be imposed on model structure for connectivity to be fully addressed. The calibration of these models should not be focused at obtaining the highest possible model efficiencies for the measured data at the outlet, but instead should be calibrated for spatial patterns of activity of overland flow, erosion and deposition using measured spatial data like DEMs of Difference and tracers.

The importance of spatial information that determines the phase of the system is shown by a recent study by Masselink et al. (2016, 2017). This study used a very simple connectivity modelling approach. The vegetation is seen as a lumped parameter with no spatial distribution. The outcome of this study showed however, that the vegetation pattern is one of the key static parameters (on the scale of discharge fluxes) that determines the flow paths in a landscape, and therefore proved to be essential to make an accurate assessment of the sediment fluxes at catchment scale. These results gave direction to which parameters in the system as essential for the water and sediment fluxes. Recent research on connectivity shows that this modelling approach can be easily applied for spatial and temporal changes in fluvial systems (López-Vicente et al., 2017; Marchamalo et al., 2016).

The connectivity framework presented in Fig. 7 can also be used to minimize model complexity, by including only the representation of connectivity phases and fluxes that are relevant at a given temporal and spatial scale. This means dividing the model to represent the relevant “connectivity structures” which include the relevant phases and fluxes. An example of how this could work is given by the CHILD landscape evolution model (Tucker et al., 2001), which uses an irregular computation mesh with more detail in areas of higher topographic complexity; a similar mesh could instead be used to represent areas of uniform or complex connectivity, in essence simulating in more detail the areas where fluxes are expected to influence phase and vice-versa. For this approach to work, it is first necessary to identify which system fluxes are relevant and need to be modelled to properly simulate transition between system phases at the desired temporal and spatial scale. This is not trivial and needs to be based on observations, which can be used to conceptualize catchment behaviour using the framework of phases and fluxes defined earlier. However, one should be careful not to limit the emergence of connectivity through over-definition. By doing so, models could become catchment-specific unless tools to understand connectivity phases and fluxes for a given catchment are readily available. The lack of spatial and temporal data for these approaches

could be overcome with an implicit approach to connectivity modelling, using the "connectivity functions" approach described by Nunes et al. (2018a), which represents highly detailed connectivity processes in an abstract way. The framework presented in Fig. 7 can support the design of these functions through a better definition of the fluxes (the object of the connectivity functions) associated with the system phase.

In order to implement the framework shown in Fig. 6, it is important to take full advantage of exiting models and data already collected by the scientific community. One important way forward is to take advantage of existing modelling frameworks that enable the coupling of existing models and data for the integrated assessment of river basins and earth systems. Examples of such frameworks are OpenMI (Argent et al., 2006; Moore and Tindall, 2005), CDDMS (Overeem et al., 2013) and Landlab (Hobley et al., 2017). Some recent examples have successfully applied these types of approaches for the integration of existing models using OpenMI for sediment transport (Shrestha et al., 2013) and integrated urban hydrologic modelling (Zhu et al., 2016). This type of framework is very useful and effective to integrate existing models and data for the study of catchment scale connectivity, and can be used for the implementation and analysis of emergent connectivity properties as envisioned in Fig. 7.

Finally, the conceptual scheme presented earlier (Fig. 7) indicates the need to introduce feedbacks between system phase and fluxes, and to simulate the co-evolution of both (e.g. patterns of vegetation, soil distribution in pockets, rock outcrops location, landforms allocation). An example of a modelling approach that simulates the coevolution of vegetation, soil and geomorphic structures is presented by Saco and Moreno-de las Heras (2013) for semiarid areas with patchy vegetation. The model intrinsically captures changes in both phase and fluxes that emerge from self-organizing principles and can be used to analyse changes in connectivity and possible links to associated threshold behaviour (Okin et al., 2015). It is also important to include co-evolution of land-use patterns for managed catchments. Again, such an approach might lead to different models for different catchments, or catchment types, to capture the most relevant processes and coevolving structures which will differ for varying environmental conditions (e.g. semiarid and permafrost catchments can represent two extreme cases). Relevant processes to include in these models depend on the temporal and spatial extent and resolution of the model Event-based models might only be concerned with changes in pathways caused by e.g. sediment deposition or landslides, longer temporal-scale models would have to include processes that capture changes in vegetation patterns, soil patterns, and topography over those time scales.

4.3. Putting it together

4.3.1. Temporal and spatial scaling issues

Following the preceding considerations on the role of connectivity in sediment and water dynamics studies we can ask ourselves the question: Does this new conceptual framework help to address up/downscaling scaling issues? For temporal scaling the conceptual model is helpful as it pulls apart the system into phases and fluxes. The phases (structural connectivity) have no temporal dimension as they are a snapshot of the system on any given time. The temporal scale of fluxes (functional connectivity) of a specific system is, as stated before, are dependent on the research question at hand.

With this definition of structural connectivity there is no dependency on time, therefore, the long-term changes of structural connectivity elements cannot be confused with functional connectivity. Instead, in the long-term, snapshots of the state (system phase, structural connectivity) can be taken at different moments in time, and changes would be described as co-evolution through interactions with the fluxes (see functional connectivity elements in Saco and Moreno-de las Heras, 2013). Changes in state will then be easier to quantify and simulate. The new definition can also help to quantify the phases and fluxes for systems in equilibrium: the minimum and maximum fluxes in the system determine the phases which act as boundary conditions for the equilibrium.

One route taken in recent studies to bridge the spatial gaps between different measurement methodologies is using, is the use of connectivity indices. Indices can be calculated both from models, as well as from measured (structural) connectivity. The index of connectivity, originally developed by Borselli et al. (2008) and later adapted by Cavalli et al. (2013) is a form of an index which uses measured structural connectivity from a digital surface model and measured soil surface roughness and/or vegetation cover. This index can be compared to an ensemble of model runs of events with varying event magnitudes to determine the connectivity of each individual location according to the model. The modelled index and the measured index can be compared with each other to learn about the system and determine which areas are important for catchment connectivity (Nunes et al., 2018b).

4.3.2. Three case studies to illustrate the framework

To illustrate the usefulness of the new framework, an example is presented of an agricultural landscape that is first reforested and in a later stage subject to recurrent fire. In this agricultural landscape the connectivity of the system is subjected to strong seasonality depending on agricultural operations and climate seasonality (Fig. 9). Agricultural management impacts tillage erosion and soil roughness as a result of agricultural practices. Other characteristics change depending on farmer's choices such as field size, row cropping, crop choice, planting time, stubble and soil cover. The boundary conditions depend on the natural conditions (climate, geology etc.) but also on the management strategies in the region. In most regions these management strategies remain stable over years or even decades, which ensures that for this case the seasonal differences can describe the system boundaries. When the landscape is reforested, the conditions change to a much more stable situation in terms of connectivity, both inter-annually as well as intra-annually. In general, the erodibility of the system is much lower due to high vegetation density and high roughness, protecting the soil against erosion. Seasonal changes of land cover and soil conditions are limited and, therefore, the system boundaries in terms of connectivity are low and stable (Fig. 9a). However, when these forested landscapes are burnt, the equilibrium in terms of connectivity of the system gets much more complex. Wildfires affect the system in multiple ways and change catchment behaviour completely, due to removal of sinks such as the vegetation and litter (interception), which creates new connectivity patterns (Moody et al., 2013). Furthermore, the (dis)appearance of soil water repellency, or the enhancement of its impacts where it is already present, can create a pattern of runoff sources which depend on soil moisture conditions and may have a markedly seasonal character (Nunes et al., 2016). Furthermore, the loss of vegetation cover can expose and enhance the connectivity effects of man-made features such as forest tracks or terraces (Shakesby, 2011). These impacts change in time according to the rate of vegetation recovery, but post-fire human management operations such as terrain preparation for replanting or erosion control measures can also markedly change connectivity (Moody et al., 2013; Shakesby, 2011). The combination of these changes to the system dynamics cause large band in which the system state moves. The system can move from being highly connected (just after a fire) to highly unconnected conditions of a full-grown forest. In addition, the variations because of seasonal weather differences are large; in the post-fire period when vegetation is regenerating, the impact of a wet or dry year can be profound; while in the full-grown forest system the same climatic variations have limited impact on the connectivity. The situation described in Fig. 9a has been tested in a catchment in Portugal (Nunes et al., 2018b). Using the SWAT model, they showed that average erosion rates from agricultural terraced fields were lower than average erosion rates of a planted eucalypt forest affected by recurrent fires every 20 years. However, if no terraces would have been present in the agricultural fields or the plantation would have been a natural forest, the boundary conditions and fluctuations of the system phase

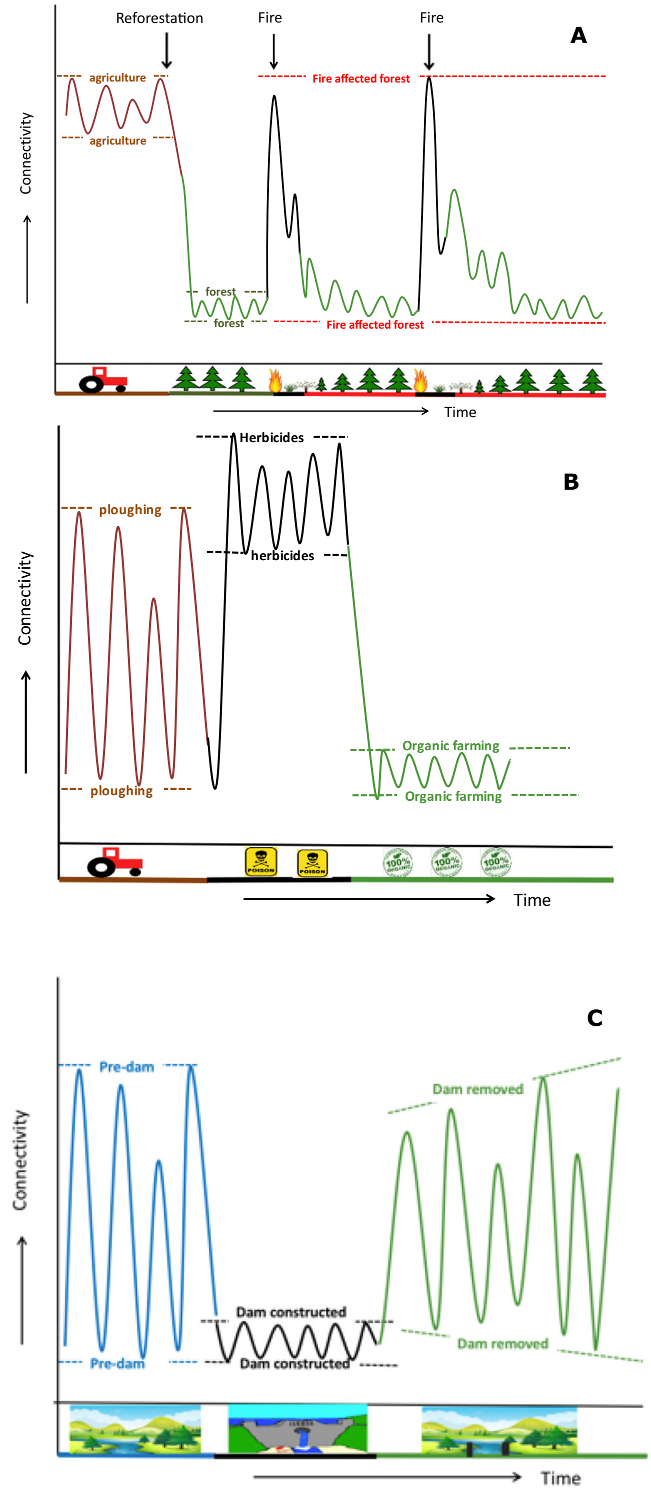

Fig. 9. Conceptual representation of connectivity variability and the boundary conditions for three different system states behaviours under three different management: agriculture, forest and fire effected forest. A: a system changing from an agricultural to a forested to a forest subdue to recurrent fire; B: an orchard changing from traditional tillage management to a no-till herbicide to an organic management without tillage. C; the impact of dam construction and removal to achieve the naturalization of a river.

would have been different, making the agricultural fields would less sustainable. In the second example, based on research in a Mediterranean apricot orchard (S Keesstra et al., 2016), the system changes between three stages: 1) from a traditionally ploughed system to, 2) an herbicide treated orchard, and 3) to an organically managed orchard without ploughing nor herbicides and with cover crops and chipped pruned branches. In the data we observe the trends in connectivity as depicted in Fig. 9b. Connectivity is low just after ploughing due to high roughness and infiltration rates, however, after a couple of rainfall events the soil is slacked and compacted which decreases infiltration, facilitating high runoff rates, and high connectivity as a result. The boundary conditions are far apart. In the plots treated with herbicides the surface is always compacted and has low roughness. In combination with the absence of vegetation cover this surface situation creates a continuously high potential connectivity. In the third example (Fig. 9c), first, a natural river is dammed and later the dam is removed. This example shows the change in longitudinal connectivity. The phase in the pre-dam system is dependent on the natural conditions of the channel and drivers of the system such as climate and geomorphological setting, this makes the system phase in terms of connectivity highly variable. When the river is dammed, the boundary conditions change dramatically as the downstream part of the river becomes regulated in terms of water and sediment fluxes and therefore the connectivity is low and stable (Poeppl et al., 2015). When the dam is removed, the system is water connectivity is immediately restored, while system recovery to a pre-dam state might in terms of sediment connectivity take many years depending on manifold factors such as dam age and size, and the environmental boundary conditions (e.g. Burroughs et al., 2009; Tullos et al., 2014; Poeppl et al., 2015). The legacy sediments from the dammed situation interfere with the sediment dynamics both up and downstream from the removed dam. Also, remains of dam related structures in the channel prohibit the river to return to its old condition. The system will not be in an equilibrium for a lengthy period of time, which has a large impact on the approach that should be taken when studying such a system.

These case studies show that boundary conditions vary between different states of a system. Being aware of the oscillations of the phase helps to design the sampling scheme, especially in terms of the minimum time of monitoring needed. In the case of an organically farmed orchard the monitoring time can be much shorter than in the case of a forest subject to fires. In the case of the river after dam removal, the river is needs time to adapt to the new situation, and because the equilibrium state has not been reached, the boundary conditions cannot be defined. Making phase graphs of historical data may prove to be useful to determine the state a system is in, and provide help to assess the monitoring length and frequency to capture the variability of the connectivity.

5. The way forward

The last objective of this paper is to identify priority research issues to advance our understanding of measuring and modelling approaches using the connectivity concept. Many questions remain unanswered, and therefore, the research agenda on this topic is still considerable. The issues that should be further addressed by the scientific community working on connectivity can be framed in several questions.

As shown by recent research, the concept of connectivity helps to comprehend the occurrence and routes of water and sediment within a system. The connectivity concept is useful to identify the dominant processes that reflect the effective fluxes in models (Bracken et al., 2013, 2015; Parsons et al., 2015). However, even though the concept has proved to be useful for assessing the system from a qualitative point of view, the quantification of these water and sediment dynamics is still under development.

A second issue is how the conceptual framework presented in this paper can be used to develop a more holistic way of looking at the various processes underlying catchment system dynamics. It is needed to look into how the framework presented in this paper, helps to build simpler measuring and modelling approaches to better represent the phases and especially the fluxes of water and sediment in a system. For measuring, the connectivity framework helps to identify parameters

and sampling strategies, which can efficiently represent catchment dynamics. For modelling, the separation between system phases and fluxes clarifies the processes driving catchment dynamics and should allow more complete, yet simpler, model structures. Can this help develop models, which can predict how a dynamic system will change under a certain external perturbation, without becoming too complex? These issues have already been raised (Costanza and Ruth, 1998; Wood and Shelley, 1999), but we believe that the conceptual framework we present helps clarify the way forward.

Lastly, how can we be sure that we really captured all the dynamics in the system? How do we assess the boundary conditions of the system we are working with? Especially in semi-arid systems this is a difficult issue, because only rare storm even trigger the system to be fully connected (Marchamalo et al., 2016). In a typical year sediment hardly moves, and only some sediment already available in the drainage system will be transported, but there is no connection within the hillslopes, or from the hillslopes to the drainage system (Ochoa-Cueva et al., 2015; Serrano-Muela et al., 2015; Masselink et al., 2017). Therefore, even decades of monitoring in such systems may not reveal the system boundaries. In these cases, measuring the phase (structural connectivity) of the system may be much more insightful than measuring the fluxes. In this way, the conceptual scheme presented in Fig. 7 may serve to identify the best parameters to focus on for each research question.

In summary, we accept that separating system phase (time-independent) and fluxes (time-variant), as described in the connectivity framework we present, will help to:

- Conceptualize our understanding of system dynamics at different time scales;
- Identify the main parameters driving system dynamics, and devise monitoring strategies which capture them; and
- Build models with a holistic approach to simulate system dynamics without excessive complexity.

The main research efforts should comprise the reanalysis of existing datasets using this conceptual framework, to gain new knowledge on the dynamics of the systems they represent; the development of new measuring approaches, which can represent the main system fluxes; and developing modelling approaches which differentiate system state and fluxes, from which connectivity features emerge. Connectivity is a useful tool concept for scientists that must be expanded to stakeholder and policymakers. Connectivity as a concept has the potential to make science understandable to the land users and plan a better land management.

6. Conclusions

Connectivity is a key concept to understand the evolution and the needs to progress of the Earth Sciences. The literature review shows that the concept of connectivity is increasingly being used, but the definitions of structural and functional connectivity are unclear and too dependent on the temporal scale of the study. This paper aimed to contribute to use connectivity in a standardized, homogeneous and consistent way. In this paper we have discussed the usefulness of the concept of connectivity for understanding, measuring and modelling water and sediment fluxes in catchment systems. We conclude that:

- We have a good conceptual understanding of the application of connectivity in the Earth Sciences, however, the existing terminology is multi interpretable.
- The current conceptual frameworks serve well to understand qualitatively the processes in catchment systems in terms of water and sediment fluxes, however, are they not usable for quantification of these fluxes.
- The above-mentioned shortcoming of the current concept description calls for a new framework, which is introduced here. In this framework the water and sediment dynamics are framed in two parts. The system is presented as one of phases and fluxes; each of these phases and fluxes are separately measurable. This enables us to:

  - Conceptualize our understanding of system dynamics at different time scales;
  - Identify the main parameters driving system dynamics, and devise monitoring strategies which capture them;
  - Build models with a holistic approach to simulate system dynamics without excessive complexity.

In this paper we discuss the system boundaries; natural systems have boundaries, which especially in (semi)-arid regions can be far apart in terms of connectivity due to extreme events which are often not measured within the timeframe of a specific project in which the fluxes of a system are measured. In those cases, it may be useful to incorporate information of the system phase (landforms and processes). The impact of external pushes (change from agriculture to forest, from forest to forest fire affected land) to the system can change the boundary conditions and change the system. This is important for setting up measuring schemes and building comprehensive models that comprise of all dynamics in a system.

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